

bation. If most Maastrichtian inoceramids were adapted to low-O environments, a reorganization of ocean circulation leading to increasing influence of oxygenated, Antarctic bottom waters fits the constraints imposed by inoceramid biostratigraphy and paleogeography. In this scenario typical inoceramids would be expected to survive longest in somewhat isolated basins in low latitudes. Regardless of the ultimate fate of this hypothesis, though, changes occurring during the mid Maastrichtian provide the opportunity to examine the interplay of ecological variables on a global scale across a geologically resolvable interval of time.

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AN EVALUATION OF CRITERIA THAT MAY BE USED TO IDENTIFY SPECIES SURVIVING A MASS EXTINCTION. N. MacLeod^{1,2}, ¹Department of Geological and Geophysical Sciences, Princeton University, Princeton NJ 08544, USA, ²Present address: Department of Palaeontology, The Natural History Museum, Cromwell Road, London, SW7 5BD, UK.

One of the most difficult obstacles to establishing a causal connection between mass extinctions and large body impacts is the existence of what appear to be many more KT survivor species than previously suspected. Though interpretations of "Cretaceous" faunal elements in lowermost Danian sediments differ, this enigmatic fauna has now been recovered from every biozone-complete boundary section, including the El Kef stratotype. In terms of their potential for providing constraints on scenarios seeking to account for the KT extinction event, the significance of such observations cannot be overstated.

Owing to the consistency with which these observations have been made over the last several years, the possibility of widespread trans-KT biotic survivorship can no longer be dismissed. Rather, the survivorship hypothesis must be tested alongside its alternative (the reworking hypothesis) to determine which explains the available data in the most complete yet parsimonious manner. Moreover, valid tests for survivorship cannot be based on negative evidence or on the assumption that only a small cohort of species could have survived the KT boundary event. Several authors have recently proposed various criteria that might be used to test alternative interpretations for this aspect lowermost Danian biotic record (Table 1). These are evaluated below.

Preservational State: The most commonly applied test for survivor identification is based on the principle that physically reworked specimens should exhibit abrasions, breaks, recrystallized surface texture, or other signs of degraded preservation. Although it is possible to collect and quantify evidence bearing on preservational state, all reports of degraded physical condition of Cretaceous species in lowermost Danian sediments offered thus far

have been qualitative and anecdotal. Nevertheless, several authors have noted that when specimens of "Cretaceous" species collected from Danian sediments are compared side by side with conspecific uppermost Cretaceous specimens, predicted differences in preservational state often fail to be observed. In addition, recent statistical analyses [1] indicate that the planktic foraminiferal survivor fauna is dominantly composed of species that are susceptible, rather than resistant, to abrasion and diagenesis.

Relative Abundance/Population Ratio: Olsson and Liu [2] explain this test as follows: "If one species survived (the KT boundary) its population size in the lower Paleocene would be composed of both the reworked and indigenous surviving fractions while that of the extinct species consists only of the reworked fraction. As a result, the relative abundance of the survivor taxon to that of the extinct species would significantly increase after the extinction of the other species" (p. 136). Applying the relative abundance/population ratio test to depositional rate-normalized KT planktic foraminiferal data of [2] and [3] shows that patterns of abrupt relative abundance decline in Danian occurrences of "Cretaceous" planktic foraminiferal species are not consistently observed for either established or putative KT survivor species. Nevertheless, patterns of post-boundary relative abundance variation exhibited by many "Cretaceous" species are indistinguishable from patterns present in widely-accepted survivor species. Overall, these data support recognition of an expanded survivor fauna and a progressive faunal turnover.

Stable Isotope Geochemistry: This test involves determining whether the stable isotopic signature of postboundary populations differs from that of preboundary populations. Recovery of different isotopic signatures from these populations constitutes a direct species-level test of survivorship. However, adequate controls must be maintained to insure that the observed difference cannot be accounted for through diagenetic or species-specific metabolic factors. Comparative analyses of planktic and benthic foraminiferal species from Brazos River (Texas), Nye Kløv (Denmark), and ODP Site 738 (South Indian Ocean) suggest that several survivor species are present in these faunas. Changes in the isotopic signatures of these survivor populations also begin in the upper Cretaceous; well below the appearance of any putative impact debris.

Quantitative Morphology: Like the stable isotope test, consistent changes in test size and shape parameters provide another means of identifying survivor species. MacLeod and Keller [4] demonstrated that lowermost Danian samples of *Heterohelix globulosa* and *H. navarroensis* from Brazos Core undergo statistically significant test size reductions, while at the same time preserving the ontogenetic trajectories of comparably sized uppermost Maastrichtian populations. Once again, this size reduction does not coincide with the KT boundary but rather takes place well below this horizon, within the uppermost Maastrichtian. Since this initial study, similar size/shape patterns have been documented for several other "Cretaceous" survivor species in other boundary sections/cores.

Comparative Biogeography: Occurrence of Danian populations of "Cretaceous" species in areas in which they were not observed during the upper Cretaceous is consistent with trans-KT survivorship. Also, comparison of changes in the biogeographic structures of survivor and indigenous Danian faunas can be used to determine whether the spatial organization of these faunas are

TABLE 1. Criteria proposed for identifying survivor microfossil species.

Criterion	Description*	Reference
Preservational state	Survivor species should exhibit a superior preservational state relative to reworked specimens.	[7]
Relative abundance/ population ratio	Survivor species will include indigenous and reworked fractions and thus will exhibit a sudden increase in interspecific relative abundance and intraspecific relative abundance (=population ratio) across the event horizon.	[2]
Stable isotope geochemistry	Survivor species may exhibit unique stable isotopic signatures.	[8]
Comparative biogeography	Survivor species may be found in previously unoccupied habitats ¹ , might exhibit unique patterns of geographic organization ² (^{1,2} relative to underlying conspecific Cretaceous fauna), should exhibit patterns of geographic organization similar to that of Danian faunas. ³	[9] ¹ [1] ^{2,3}
Quantitative morphology	Survivor species may exhibit changes in size or shape.	[4]
Association with Ir anomaly	Survivor species should persist above the level at which Ir values (or Ni-rich spinel abundances) have returned to background levels.	Modified from [10]
Synchronous last appearance datums (LADs)	Survivor species should exhibit synchronous LADs throughout their geographic range.	[9]
Phylogenetic ancestry	Incoming species should be derived from survivors.	[9]

* Only positive evidence can serve as a reliable indicator of survivorship owing to the inherent ambiguity of negative evidence (e.g., unchanged stable isotopic signature in both preboundary and postboundary populations).

similar (suggesting survivorship) or different (suggesting reworking). MacLeod and Keller [1] and MacLeod [5] have carried out an extensive series of analyses designed to implement this test. Results show that (1) many "Cretaceous" taxa occurring in the Danian portions of various boundary sections are not present in underlying Cretaceous strata, (2) a close and predictive association exists between "Cretaceous" and indigenous Danian species richness values throughout the lower Danian, (3) a close geographic correspondence is present between centers of Danian planktic foraminiferal speciation and the disappearance of "Cretaceous" species from the Danian fossil record, and (4) a pronounced similarity exists between changes in the general biogeographic structures of "Cretaceous" and indigenous Tertiary faunas throughout the lowermost Danian. Furthermore, these data show that the KT planktic foraminiferal extinction event exhibited a marked geographic structure with low- and middle-latitude faunas experiencing differentially high extinction rates in the lowermost Danian zones P0 and P1a and high-latitude survivor faunas persisting relatively unchanged into the overlying Danian.

Association with Elevated Ir Abundances: This test argues that Cretaceous faunas occurring in lower Danian sediments in which elevated (= nonbackground) levels of Ir also occur should be regarded as reworked. There are several problems with the use of this test. Association of "Cretaceous" morphotypes with elevated abundances of Ir in lowermost Danian sediments is indeterminate with respect to the question of survivorship. Bolide-introduced Ir can diffuse through undisturbed sediments via interstitial fluids [6] while fossils require physical disruption of the sediment to be reworked. Moreover, many lines of evidence indicate that the KT Ir

anomaly reflects input of Ir into the environment from multiple sources over a considerable time interval. Assuming that stratigraphic thickness of the Ir anomaly might place an upper limit on the reworking depth, though, continued occurrence of "Cretaceous" morphotypes above the Ir anomaly constitutes evidence for survivorship. Using this test almost all Danian occurrences of "Cretaceous" taxa, regardless of taxonomic group, are identified as survivors.

Synchronous Last Appearance Datums (LADs): This test suggests that true survivors should have synchronous LADs. Both the International Stratigraphic Guide and the North American Stratigraphic Code agree that the boundaries of most biozones, unlike the boundaries of chronozones, are characteristically and conceptually diachronous. Thus, there is no justification for the idea that synchrony of local LADs, or lack thereof, can play any role in deciding the question of survivorship. This conceptual distinction between biostratigraphic and chronostratigraphic units is also borne out by the large number of high-resolution biostratigraphic studies that routinely document substantial diachrony in paleontological datums.

Phylogenetic Ancestry: This proposed test is based on the principle that incoming species must be derived from survivor species. Of course, the phylogeny test is irrelevant to determining the survivorship of Cretaceous species that may have existed in the lower Danian but failed to give rise to any fully Danian descendants. A more serious problem, however, lies in the fact that phylogeny can only provide a relative ordering, rather than the absolute temporal location, of speciation events. These problems, along with present levels of indeterminacy with respect to the species-level phylog-

enies of virtually all trans-KT clades, invalidate this application of phylogeny to the question of survivor identification.

The unambiguous identification of KT survivor species is extremely difficult. But, as outlined above, criteria are available to test the survivorship/reworking alternatives at both the individual species and faunal levels, though not all tests that have been proposed are adequate on theoretical or phenomenological grounds. While much more work needs to be done on this question, the data presented above demonstrates that there is a large body of evidence consistent recognition of a greatly expanded survivor fauna that dominated both marine and terrestrial ecosystems during the earliest Tertiary.

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THE "UPPER CRETACEOUS UNIT" IN THE CHICXULUB MULTIRING BASIN: NEW AGE BASED ON PLANKTIC FORAMINIFERAL ASSEMBLAGE. L. E. Marín¹, V. L. Sharpton², J. Urrutia-Fucugauchi¹, P. Sikora³, and C. Carney³.

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The Chicxulub structure is now recognized as one of the largest multiring impact basins on Earth with a corresponding age of 65 m.y. [1]. It has been interpreted as the source of the KT ejecta layer. However, some doubt has been expressed as to the age of the structure because "Upper Cretaceous" fossils were reported 355 m above what is now known to be the impact melt in the well Yucatan 6 [2]. However, samples recently released by Petroleos Mexicanos (Pemex) to the Universidad Nacional Autónoma de México have allowed us to examine closely the core immediately above the impact rocks in the Yucatan 6 well. The so-called Upper Cretaceous limestone unit is represented by core interval (nucleo) 12 recovered from a depth 1000–1003 m below sea level. This unit is a fine-grained well-indurated white limestone with visible laminations demarcated by dark gray fine-grained material, possibly clay. Original records indicate that a 2-cm-thick bentonite layer is located near the top of this core interval. The next core interval down from N12 was recovered from a depth 1100–1103 m below sea level. N13 was previously listed as a green bentonitic sandstone unit of Upper Cretaceous age, but our analysis indicates that this is a sand-sized impact breccia containing shocked mineral clasts and partially altered glass in a carbonate-rich matrix.

Thin sections of two N12 samples (part 11 and part 12) near the base of the core interval were examined. The fossil assemblage consists mainly of abundant planktic foraminifera of the genera *Globigerina* and *Globorotalia*. The following age-significant spe-

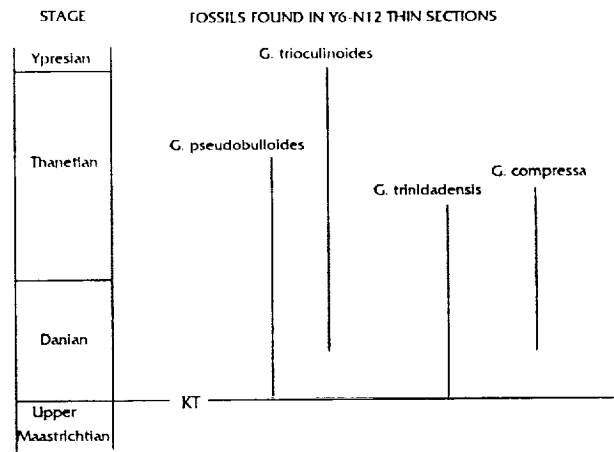


Fig. 1.

cies were identified: *Globorotalia pseudobulloides*, *Globorotalia trinidensis* (or possibly *Globorotalia uncinata*), and *Globigerina triloculinoidea*. Each of these forms has the base of its stratigraphic range in the lower Danian; the youngest base is that of *G. compressa*. The tops of their ranges are mostly in the lower Thanetian; the oldest top is that of *G. trinidensis* in the lowermost Thanetian. Thus, the most likely age for these cores is Middle-Lower Danian to lowermost Thanetian. These age assignments rely on the stratigraphic ranges of these species in Amoco's Corporate Composite Standard Database, but can be referenced to (Blow's) Planktonic Foraminiferal Zones [e.g., 3]; either middle P1 through Middle P2 if we have *G. trinidensis* or Lower P2 through Lower P3 if we have *G. uncinata*. Either alternative yields Lower to Lower Middle Paleocene (Fig. 1).

At the time of deposition, the water depth at this spot was at least 100 m. This is based on the abundant occurrences of planktonic forams in general. Frequent occurrences of *Globorotalias* suggest somewhat deeper water environments, maybe outer neritic—approaching 200 m. We observe a single specimen that appears to be *Nuttallides* (benthic). If this interpretation is correct, an upper bathyal environment is implied. More work is needed, however, before a positive identification of *Nuttallides* can be made.

The work presented here shows that the so called "Upper Cretaceous" fossil assemblage found above the impact melt has an age corresponding to the Lower Tertiary. Thus, the age of this unit is consistent with Chicxulub being temporally linked to the KT boundary, as radiometric and paleomagnetic data have indicated.

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